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REPORT

**DIGITAL VIDEO:comb filtering
in sub-Nyquist PAL codecs**

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Summary

It is possible in theory to reduce the slight impairment introduced by line-delay comb filters in a sub-Nyquist PAL codec by using alternative forms of comb filtering. A description is given of the theoretical effects of line-delay, field-delay and picture-delay comb filters. A brief experimental investigation of the effect of a field-delay filter compared with a line-delay filter in the decoder showed that although the expected changes were visible on special test pictures no significant differences were seen on typical (but critical) television pictures. However, further work is considered desirable to extend the investigation to both pre- and post sampling filters, including picture-delay filters, and to PAL signals for which cross-colour has been reduced.

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1. Introduction

A previous Report¹ has described a method of sub-Nyquist sampling of composite PAL colour video signals. It is attractive since sampling can be at $2f_{sc}$ * instead of say $3f_{sc}$, thus giving a considerable saving in bit rate. The main impairment introduced by the technique is a slight loss of diagonal luminance resolution; there is also a slight loss of vertical chrominance resolution. These losses result from the use of comb filters, incorporating a one line-period delay, in both the digital coder and decoder.

The use of comb filtering is an essential part of the method but filters using a field or picture delay rather than a line delay might offer better picture quality. This Report describes a brief investigation of this hypothesis.

2. The use of comb filtering in the sub-Nyquist technique

2.1. The need for comb filtering

The comb filter in the decoder serves two main purposes:

- (i) It removes unwanted luminance alias components occurring at frequencies $(n + \frac{1}{2})f_L$, where n is an integer and f_L is the line-scanning frequency.
- (ii) It reconstructs chrominance information of the standard PAL form from the non-standard signal which is actually transmitted when using the sub-Nyquist technique.

Luminance information in a composite PAL video signal is primarily clustered around harmonics of f_L , with a minimum of energy in between, i.e. at $(n + \frac{1}{2})f_L$. This is exploited in the sub-Nyquist system in which the sampling frequency $f_s = 2f_{sc} \approx 567\frac{1}{2}f_L$, an odd multiple of half line frequency. With this relationship between f_s and f_L the alias components resulting from the sampling of high-frequency luminance information will tend to be clustered at odd multiples of half line frequency, i.e. at $(n + \frac{1}{2})f_L$, with a minimum of alias energy at line frequency harmonics, nf_L . Thus, after sub-Nyquist sampling of a luminance-only signal, there exists predominantly wanted information around nf_L , and predominantly unwanted alias signals around $(n + \frac{1}{2})f_L$. The latter may be removed by a comb filter having nulls at $(n + \frac{1}{2})f_L$, leaving a signal containing most of the original information. In practice there is no need for comb filtering below 3.37 MHz since, for the sampling frequency of $2f_{sc}$ (8.87 MHz), the overlap region in which alias components fall extends upwards from 3.37 MHz (i.e. $8.87 - 5.5$).

* f_{sc} = PAL subcarrier frequency = 4.43361875 MHz for System I.

The precise phase of sampling which is used in the technique causes the sub-Nyquist signal to have a colour subcarrier of uniform phase which carries $(U + V)$ and $(U - V)$ information on alternate lines. It is thus necessary to recombine information from pairs of lines, one bearing $(U + V)$ and the other $(U - V)$, in order that the final result may have the usual U and V information in quadrature on every line. This is the second purpose of the decoder comb filter.

We have so far considered the comb filter which is essential in the decoder. However, there are advantages in passing the signal through a comb filter in the coder also, before sampling. Consider first the behaviour in respect of high-frequency luminance information. We have assumed that the original signal has negligible energy at $(n + \frac{1}{2})f_L$, i.e. between line-frequency harmonics. This is not quite true, and the small signal components at these frequencies will appear at the decoded output as alias components at nf_L . These cannot be removed by any form of filtering at the decoder without losing the wanted signals at nf_L but their generation can be prevented by comb filtering *before* sampling, with the same form of frequency response as used for the decoder comb filter. As well as reducing aliasing caused by certain picture components there is also a slight reduction of source noise when comb pre-filtering is used.

Another advantage of the pre-sampling filter concerns the chrominance information. The working of the sub-Nyquist system depends on sampling the signal at a particular phase relative to the chrominance subcarrier. Without a pre-sampling filter, the U and V components are each sampled at instants 45° away from their peaks, near the region of maximum slope, thus demanding accuracy in the phase of sampling. However, when a pre-sampling filter is used, sampling occurs at points of zero slope corresponding to the peaks and troughs of the subcarrier, which then has uniform phase; the need for extreme accuracy in the phase of sampling is therefore greatly reduced.

2.2. Line-delay filters

What exact form of filter should be used? The simplest solution, as far as luminance is concerned, is to have nulls at the required frequencies, i.e. $(n + \frac{1}{2})f_L$, and nowhere else. This may be done by averaging the signal before and after it passes through a one line-period delay. The elegance of this method¹ lies in the fact that a simple filter like this also serves to reconstruct the colour information, given a very slight modification. The delay element used in the filter is made to be 283.75 subcarrier periods long; this is just shorter than one line period, which is 283.7516 subcarrier periods. Reference 1 demonstrates by means of vector diagrams how such an arrangement reconstructs the correct form of chrominance information, with U and V information in quadrature on every line. The

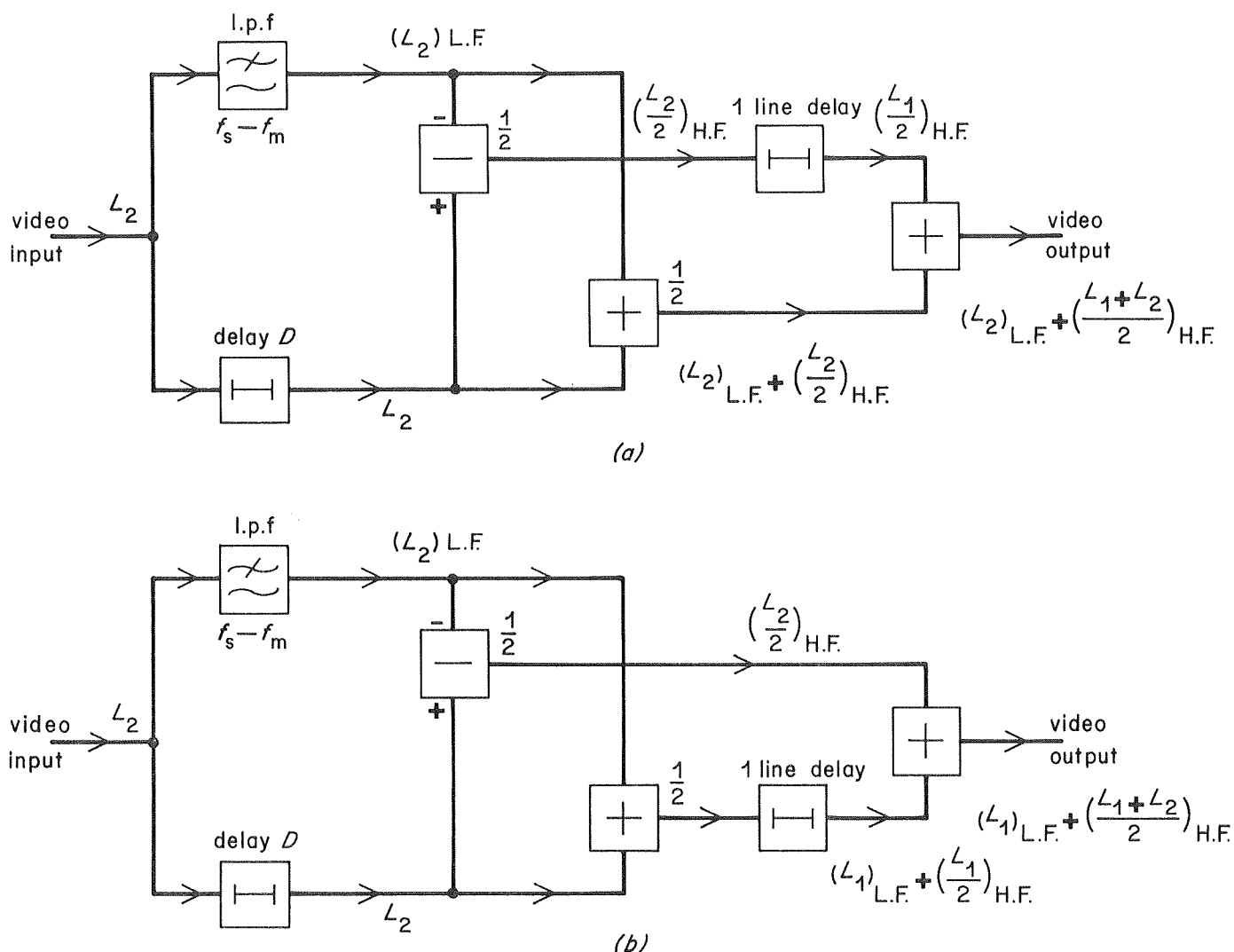


Fig. 1 - Two forms of comb-filtering using a one-line delay. L_1 and L_2 respectively indicate signals on two successive lines
 (a) Low frequencies undelayed (b) Low frequencies delayed by one line-scan period

small offset has no significant effect on the efficiency of luminance transmission. As mentioned previously, no comb filtering is necessary below 3.37 MHz, either for alias removal or chrominance reconstruction. Fig. 1(a) shows the block diagram of the post-sampling filter used in the original method, including means whereby comb filtering only occurs at the higher frequencies, and Fig. 1(b) shows the arrangement used for the pre-sampling filter. The amplitude-frequency response of the two filters is the same but the relative delay between low and high frequencies is reversed so that the two together have a uniform group-delay response and maintain vertical registration between luminance and chrominance components.

2.3. The impairments introduced by line-delay comb filters

The effects of the line-delay filters on picture quality could, in principle, be inferred from their amplitude-frequency response. However, this would involve a relationship, which is difficult to visualise, between video frequency and two-dimensional spatial frequency. It is

perhaps easier to work from first principles, inferring the spatial frequency response directly from the filter configuration.

2.3.1. Impairment of luminance signal

Consider the luminance signal first, with a single comb filter of the line-delay type. When the picture brightness varies only slowly along a scanned line the corresponding video signal is of low frequency and is unaffected by the filter. An area with rapid changes in a horizontal direction gives a high-frequency video signal which is subjected to the comb-filtering process. In effect the high-frequency detail is averaged between successive scanned lines. Now consider various orientations of a fine grating pattern. If its lines are horizontal there is no detail along a scanning line so that the signal is of low frequency and the filtering has no effect, as already noted. If the lines of the grating are vertical, the detailed variation along a line gives rise to a high-frequency signal. However, the signal on two successively scanned lines is then identical anyway so that it is unaffected by averaging. Averaging only has an

effect when there is rapid variation horizontally as well as variations in a vertical direction, i.e. with finely-spaced *diagonal* lines or with a sharp *diagonal* edge.

If both pre- and post-sampling comb filters are used the impairments introduced are effectively doubled, but the resulting overall impairment is still however relatively small. An impairment grade of 1.5 on the EBU six-point scale (≈ 4.6 on the CCIR five-point scale) was obtained from subjective tests using an 8-bit p.c.m. codec.¹ However, some of the impairment was due to the presence of two sharp cut-off 5.5 MHz low-pass filters associated with the p.c.m. codec rather than the comb filters themselves.

2.3.2. Impairment of chrominance signal

An analysis of the impairment caused to the chrominance signal by line-delay comb filters is given in Reference 1. This shows that, because of the averaging of the chrominance signal on successive lines, with no distinction between its coarse or fine detail, the main impairments are a loss of vertical chrominance resolution and the introduction of unwanted components in the region of horizontal colour transitions. These cause a $12\frac{1}{2}$ Hz flicker at the horizontal boundaries between areas of different colours, usually visible only on sharp transitions between certain highly-saturated colours.

2.4. Other possible filters

The qualitative impairments introduced by the original one-line delay comb filters have been discussed in the previous Section. Different forms of comb filter will now be considered.

In the sub-Nyquist sampled signal alternate lines convey $(U + V)$ and $(U - V)$ chrominance components; the post-sampling comb filter must therefore average a pair of lines one bearing $(U + V)$ and the other $(U - V)$ in order to obtain the normal separate U and V components at the decoder. In other words the delay in the comb filter must be approximately equal to an odd number of line periods. The original filter employing a one-line delay is the simplest example of this condition.

An obvious further requirement is that the pair of lines which are being averaged must be spatially close in order to minimise loss of definition.

Two other possible delay values which fit the requirements are: a delay equal to a whole field period plus a half-line period (i.e. precisely 313 lines)² and a delay equal to a whole picture period (i.e. precisely 625 lines).³ The potential advantage of these alternative filters is that *at least for stationary pictures* the impairments introduced would be less than the corresponding impairments for a line-delay filter. Indeed for the 625-line delay no impairments would be expected at all. For moving pictures, however, new degradations would be expected in view of the relatively long time interval over which picture information is being averaged.

Any of the above three filters can be realised in either analogue or digital form; in either case the only difference between the three is in the length of delay.

Some quantitative information on the effect of comb filtering on luminance resolution can be obtained by considering a zone plate.*⁴ For simplicity we shall consider only a monochrome system and we shall also neglect aliasing effects arising from the scanning process.

Fig. 2(a) shows the appearance of the displayed zone plate when the signal is passed through a simple horizontal low-pass filter. The rings are fully defined within the pass-band whilst the display is a uniform grey in the stop band. The transition would occur along the vertical line corres-

* The zone plate is fully described in Reference 2; briefly it is a pattern comprising concentric alternate black and white rings of increasing radius with the circular zones of constant area. The pattern so formed is a two-dimensional linear frequency sweep.

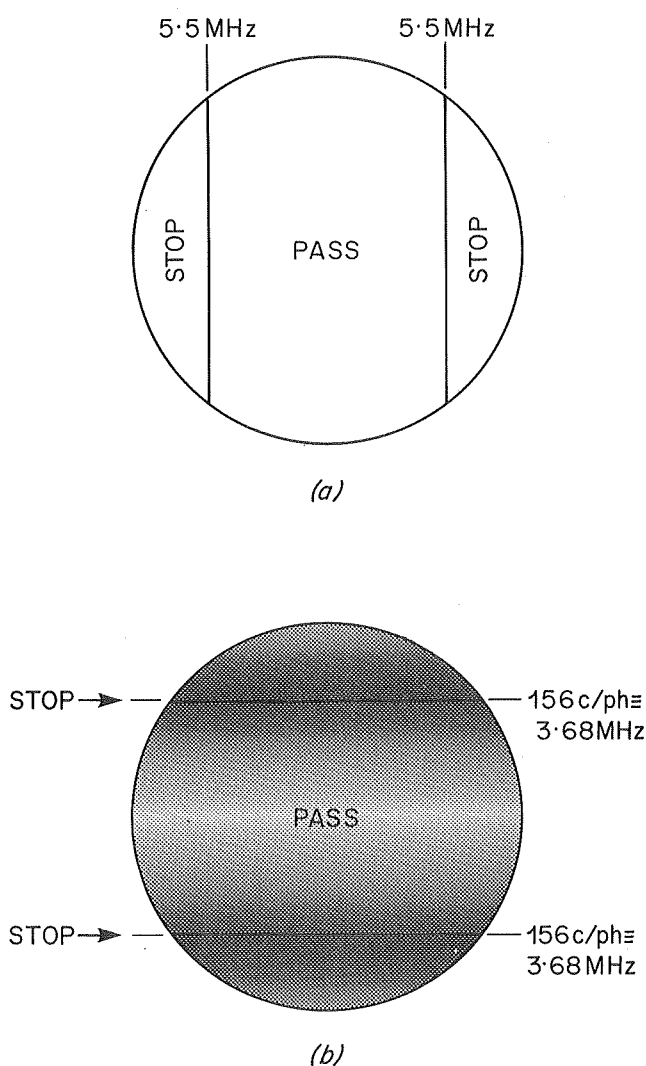


Fig. 2 - Effect of filters on a zone plate display
(figures apply for System I)

(a) Effect of simple horizontal low-pass filter on zone plate display
(b) Effect of full-band, line-delay vertical filter on zone plate display

ponding to 5.5 MHz in a System I television system. For a vertical filter, i.e. a filter obtained by combining signals from successive television lines, the display would appear as shown in Fig. 2(b). For a full-band, line-delay, comb filter there would be two horizontal bands centred on a frequency of 156 c/ph* (which is equivalent in horizontal resolution terms to 3.68 MHz) at which there would be complete loss of vertical definition. For a full-band, field-delay comb filter the bands of loss of definition would be further from the centre of the zone-plate display and the stop-frequency would be 312½ c/ph ($\equiv 7.36$ MHz) at the limit of vertical definition for a 625-line raster. For a full-band, picture-delay comb filter no loss of vertical definition would occur.

* Cycles per picture height; the figures given conform to the convention adopted in Reference 2 which ignores the effect of vertical blanking.

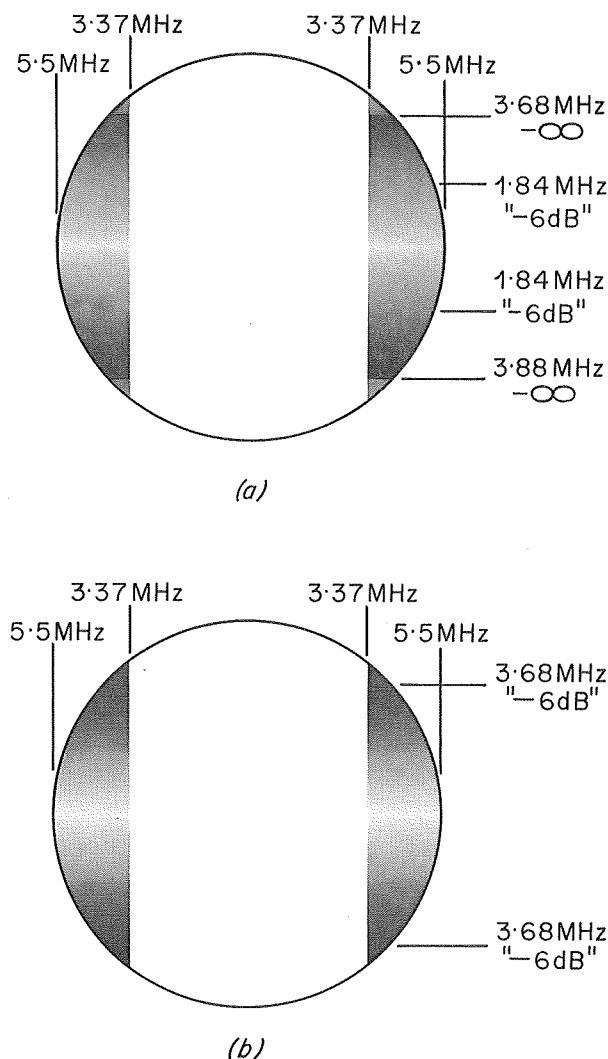


Fig. 3 - Effect of sub-Nyquist PAL system filters on a zone-plate display
(a) Effect of line-delay comb filters
(b) Effect of field-delay comb filters

In a sub-Nyquist PAL system the comb filtering need not be full-band and is normally restricted to the horizontal frequency range of 3.37 to 5.5 MHz (see Section 2.1). The effect of this on the zone-plate display is illustrated in Fig. 3 in which the zone-plate radius corresponds to the 5.5 MHz bandwidth limit for a System I standard. The '-6 dB' figures neglect the effect of gamma correction on the signals on which the filters operate. The frequencies indicated for the '-6 dB' regions assume the use of pre- and post-sampling comb filters. For post-sampling filtering only, the '-6 dB' figure would be changed to '-3 dB'. Fig. 3 indicates the considerable improvement in luminance resolution that field-delay comb filters would be expected to give on the special zone-plate test pattern. However, what is of greater interest is the improvement given on real television pictures and, in particular, the effect of picture movement. The latter would of course be expected to be more serious with picture-delay comb filters. In general, because the comb-filtration is applied only to the higher frequency signals (i.e. 3.3 MHz upwards) some disassociation between low-frequency and high-frequency picture content would be expected. For example, the verticals on a horizontally-moving, sharp-edged block would be preceded and followed by 'rings'.

So far the effects of field- and picture-delay comb filters have been considered in relation to luminance resolution. However, the use of such filters would also be expected to reduce impairments on the chrominance signal - at least on stationary pictures. It is not as easy to present quantitative information as for the luminance signal but in general the field-delay comb filter would be expected to halve the loss in vertical definition and the vertical distance over which the flicker effects described in Section 2.3.2 occur. For picture-delay comb filters the impairments would disappear. Again however, new impairments from picture movement would be expected. Because all chrominance information is comb-filtered there would be a disassociation from accompanying low-frequency luminance information. Thus a moving coloured block would have colour 'leaking' from it along the axis of movement.

In view of the difficulties in quantifying the effects of field-delay and picture-delay comb filtering especially with moving pictures, it was considered desirable to carry out an experimental assessment; a brief initial investigation is described in the next Section.

3. Experimental investigation

Only a brief investigation has so far been conducted, restricted to the use of a single field-delay comb filter.

3.1. Experimental arrangement

The field-delay used was one half of the first BBC Research Department solid-state picture store.⁵ A block diagram of the basic experimental arrangement is given in Fig. 4. Since only one field delay was available no pre-sampling comb filter was used, hence the input sampling phase was adjusted to be accurately at the 45° point on the chrominance components of the input signal.

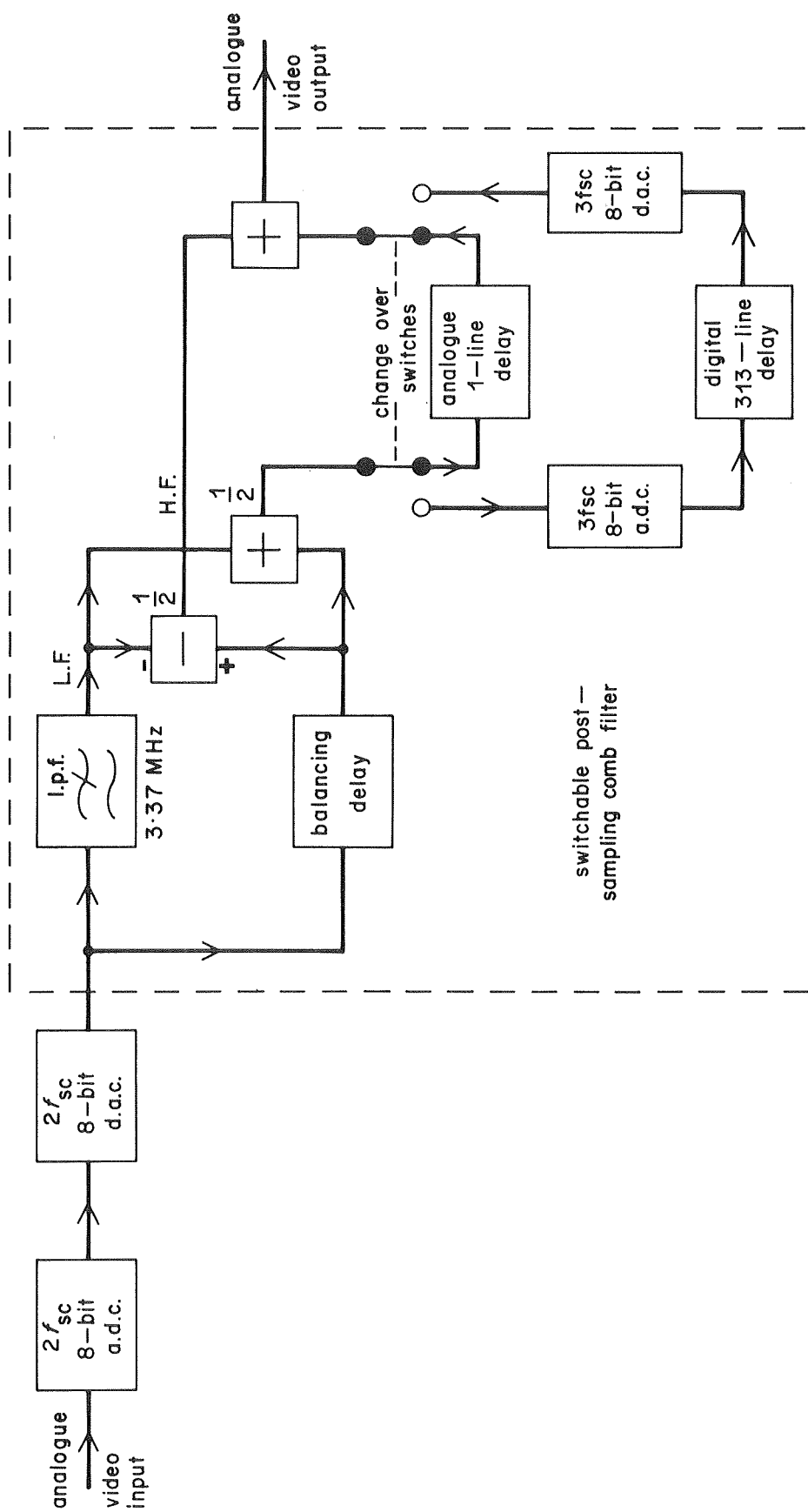


Fig. 4 - Experimental arrangement

For speed and convenience 'analogue' interfacing with the field delay was effected using $3f_{sc}$, 8-bit coding as shown in Fig. 4. The alternative would have been to embody the field delay in an all-digital post-sampling comb filter but this would, in any case, have introduced confusion into the comparison with the existing line-delay comb filter because of possible differences in the cut-off characteristics at each end of the combed band.

Quantising of the $2f_{sc}$ -sampled signal was not necessary for the experiment but again, in the interests of speed and convenience, it was decided to use the complete $2f_{sc}$ codec system.

3.2. Observations

No formal subjective tests were carried out; the following results were observed by a small group of expert viewers in unmeasured but 'reasonable' viewing conditions.

3.2.1. Stationary pictures

Monochrome and colour monitor pictures were observed using BBC Test Card 'F', 'Car Park Scene'* and 'zone-plate' signals from a slide scanner; standard System I PAL coding was used with full luminance bandwidth. Electronically-generated colour chequer-board and monochrome bar signals were also examined.

In general, all the improvements predicted in Section 2.4 in changing from a line-delay to a field-delay filter could be discerned on the test-pattern signals although the presence of residual aliasing and cross-colour effects tended very much to mask the changes. A slight improvement in general resolution was just discernible on the Test Card 'F' and 'Car Park Scene' slide pictures.

3.2.2. Moving pictures

Several types of moving pictures were observed, including: controlled repetitive movement of Test Card 'F' (produced electronically by modulation of the slide-scanner scanning waveforms); camera signal of swinging coloured bottle; electronically-generated moving bars; 'off-air' television pictures.

In general with the field-delay filter in use movement defects were readily visible on the somewhat artificial test pictures. Ringing effects preceded sharp vertical or near-vertical edges with horizontal movement. The predicted colour-smearing effect was also observed.** With typical 'off-air' television pictures however, no movement defects were seen but the period of observation was relatively short, about fifteen minutes total.

* A general view containing considerable fine detail of about 100 cars with a background of trees.

** The movement defects were asymmetrical because only one field-delay filter was employed and the configuration was such that low-frequency information was delayed relative to high-frequency information.

3.3. Discussion of results

The general feeling of observers was that on test pictures the slight resolution improvement which was seen on stationary pictures by changing from line-delay to field-delay filtering was heavily offset by the defects easily seen on moving test pictures. With typical 'off-air' television pictures it was not possible to see any differences in changing from one filter to another.

It must be noted that the presence of cross-colour tended to mask the effects of field-delay comb filtering. The results would be somewhat modified if the experiment were repeated on PAL signals for which the cross-colour was reduced either by a simple luminance notch filter in the coder or by sophisticated pre-filtering techniques.⁵ It is possible that with such 'clean PAL' signals the benefits of field-delay filtering might be more apparent, but then so would the movement defects. Further investigation is desirable to explore both this aspect, the use of both pre- and post-sampling field-delay comb filtering, and also the use of picture-delay comb filtering. With the latter it is probable that movement impairment would be visible even on typical television pictures.

It is of interest to note that a 'mixed' filter is possible whose output is given by $xL + (1 - x)P$, where L is the output of a line-delay comb filter and P is that of a picture delay comb filter, x denoting the proportion of L . The use of a mixed filter may solve the problems of movement impairment with picture-delay filtering. A fixed value of x might be found which gives an adequate compromise between resolution loss (i.e. when x is large) and movement impairment (i.e. when x is small). Failing this an adaptive strategy could be devised in which x is varied according to the degree of movement so that minimum impairment is visible in all picture areas.³

4. Conclusions

A description is given of the effects of comb filtering in the sub-Nyquist-sampled PAL coding system, and the results are given of a brief investigation into the use of a post-sampling comb filter employing a field delay rather than a line delay. It is concluded that little advantage would result from the use of field-delay comb filters on typical television pictures using present PAL coding techniques. Further work is considered desirable however with both pre- and post-sampling field-delay comb filters and also with picture-delay filters. A further investigation should also examine the effects of such filtering on the performance of possible future 'clean PAL' coding systems.

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